MSL Mission Planning & Execution

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Motivation

- A framework for planning, scheduling, and execution.
- A control centered approach toward representing plans as opposed to an action centered approach
- This is the current default system for flying onboard the MSL rover.

Outline

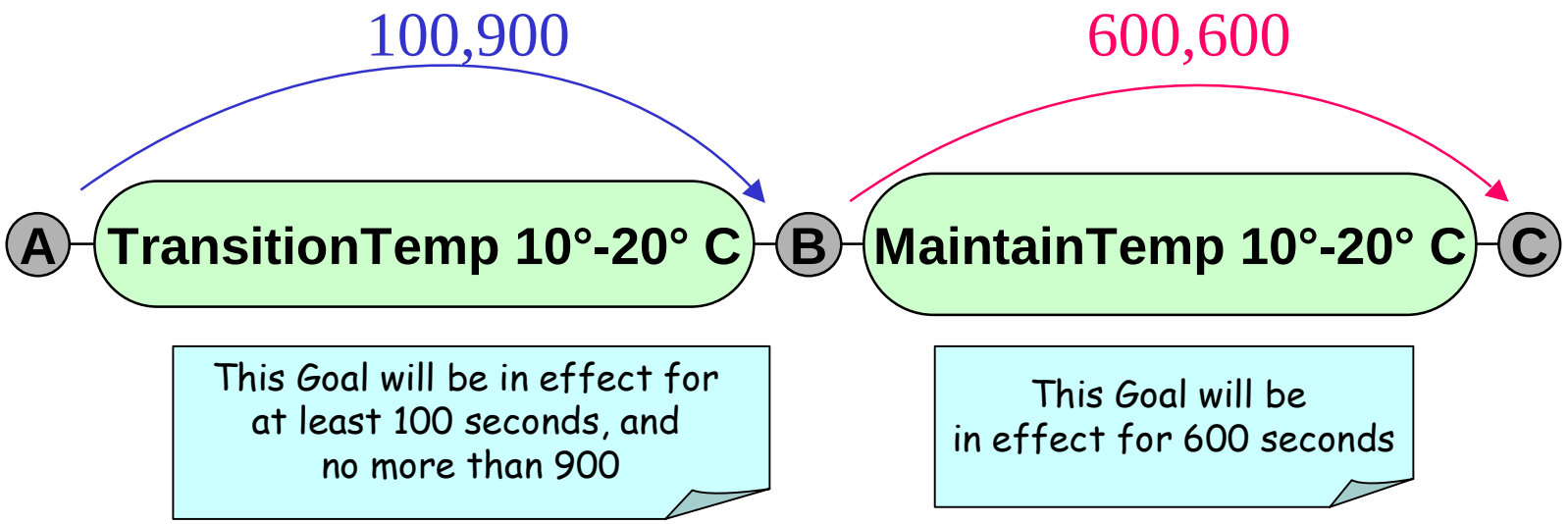
- Plan/problem representation
  - Partially ordered constraints on state variables.
- MPE component architecture
  - Numerous threads of execution
- Elaboration & Scheduling
  - Subsumes both PO and HTN planning
- Plan execution
  - Firing time-points & enforcing constraints

The Problem

- Givens
  - A model of how state variables affect each other
  - Tactics for elaborating constraints into supporting constraints.
  - A temporally constrained set of commanded constraints on state variables.
- Objectives
  - Elaborate the constraints into an executable network, where constraints can be incrementally passed to controllers for each state variable.
  - Execute the elaborated network.

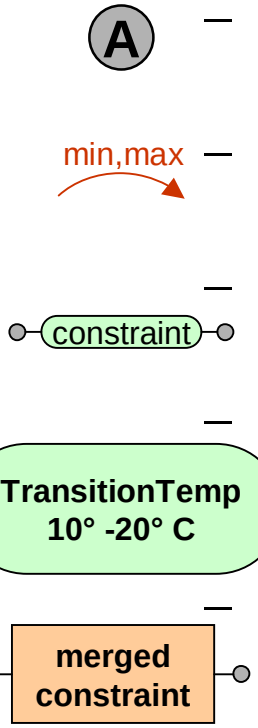
Plan/Problem Representation

- A network of timepoints connected by temporal and state-variable constraints.

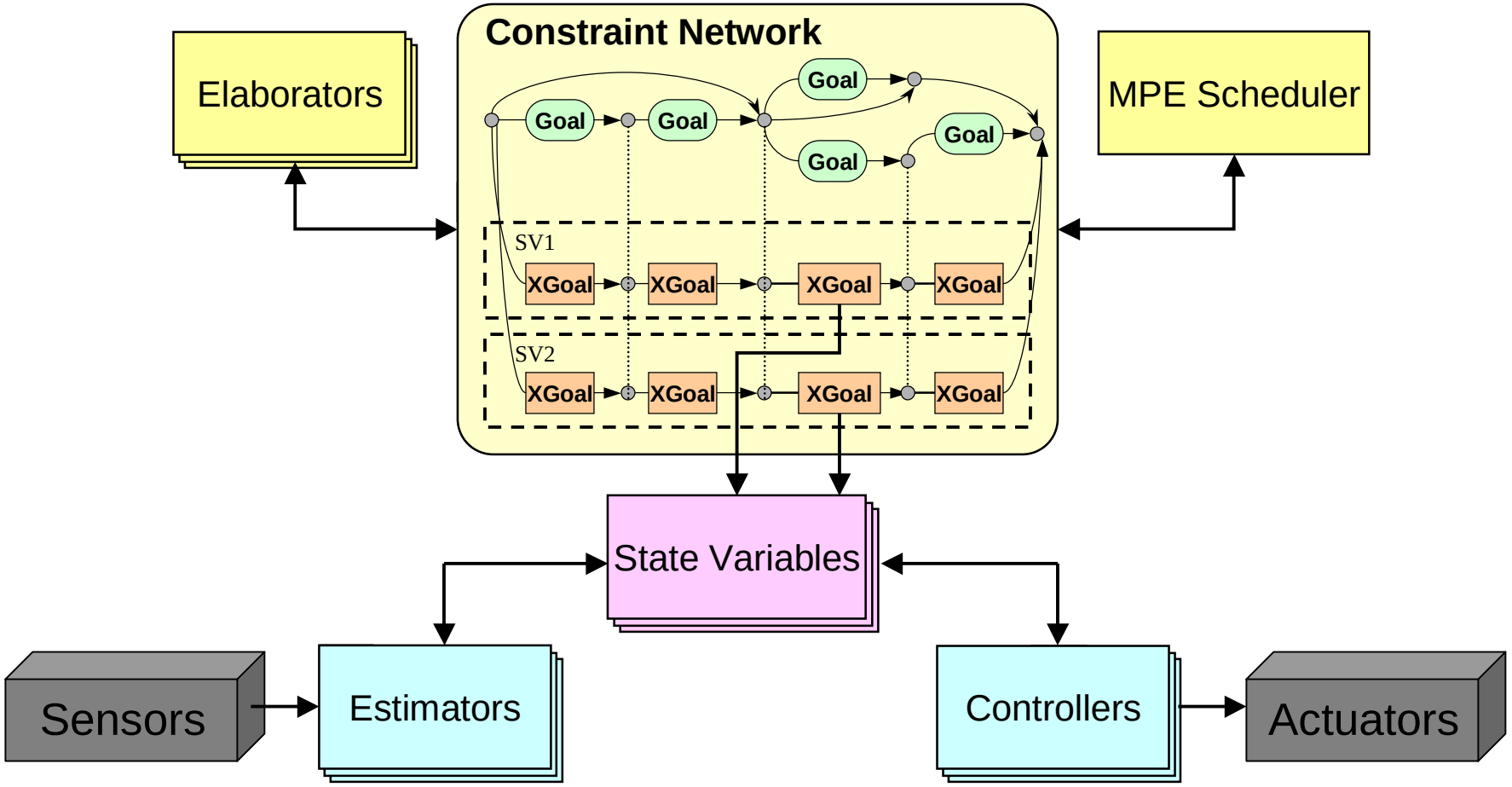


Plan/Problem Representation

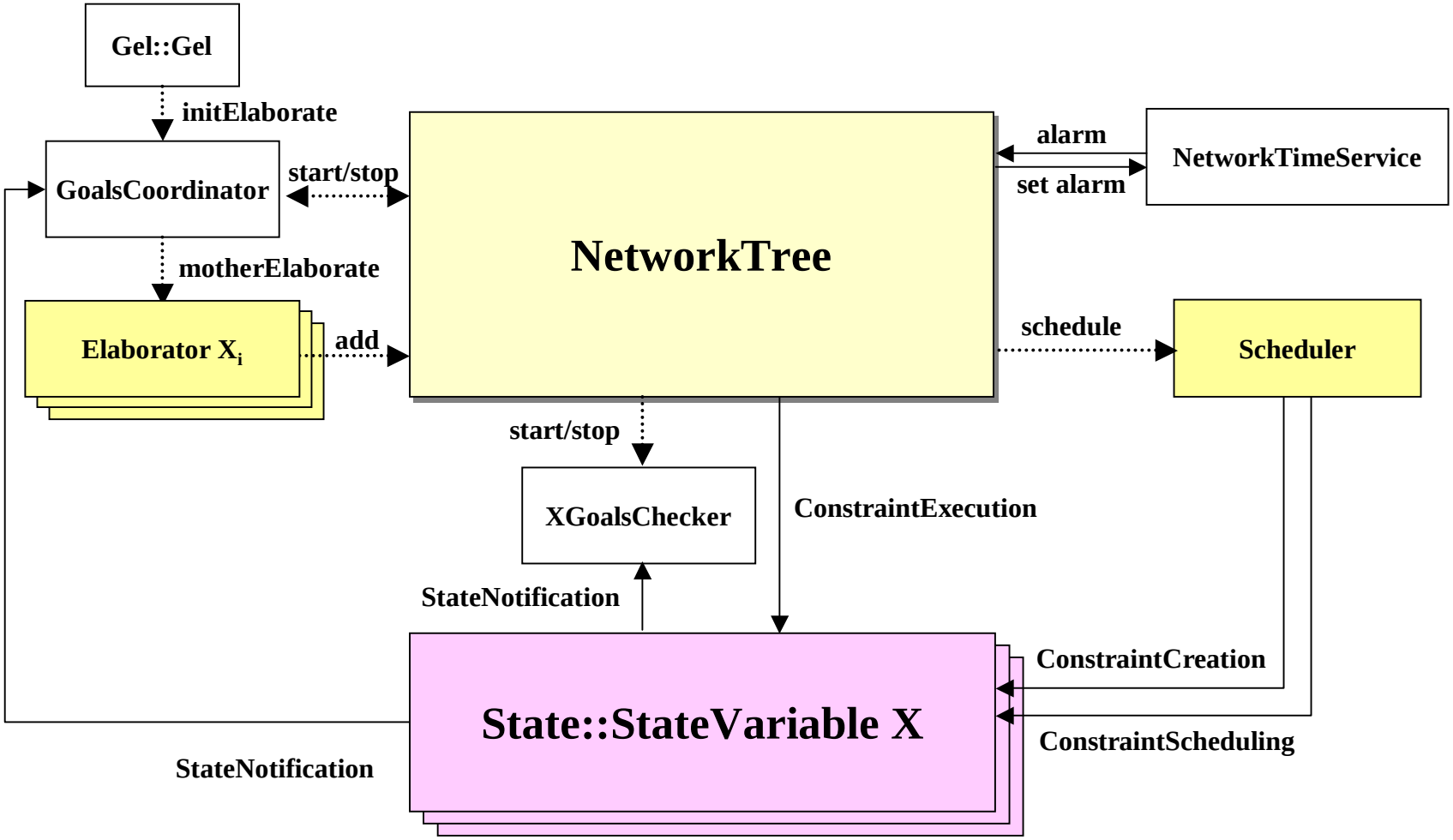
- Definitions
  - Timepoint
    - A flexible point in time
  - Temporal Constraint
    - A timing relation between two Timepoints
  - Goal
    - A State Constraint over a time interval demarcated by two Timepoints
  - State Constraint
    - A representation of a set of values, used to specify a required (allowable) state
  - Executable goals (xgoal)
    - A merged state constraint that can be passed to a state variable controller

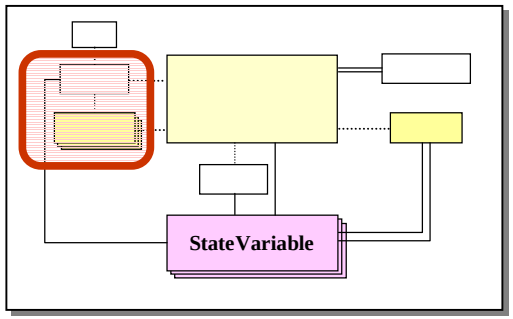


MPE Component Architecture



Actual MPE Components
(each has an execution thread)

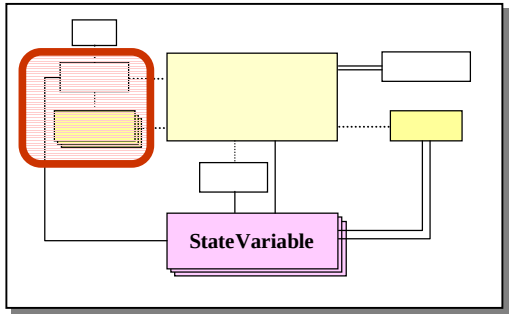




Elaboration

- Objective
  - ➢ To set up conditions where a state variable's controller can enforce a goal's constraint.
- Algorithm

Copy task network to proposed network for modification
While there are goals to elaborate do
  Choose a goal **G** to elaborate (from a heuristic ordering)
  Exhaustively choose elaboration tactic **E** for **G**
  Apply **E**, which possibly generates new goals to elaborate
    – Backtrack if application of **E** illegal



Elaboration

GoalsCoordinator

proposerRequest

proposerStatus

promote

NetworkTree

New
Executing Network

Communicating

Elaborator

elaborate

add(Goal, T1, T2)

Maintain attitude

Elaborator

elaborate

add(Goal, T1, T2)

Turn

Elaborator

add(Goal, T0, T1)

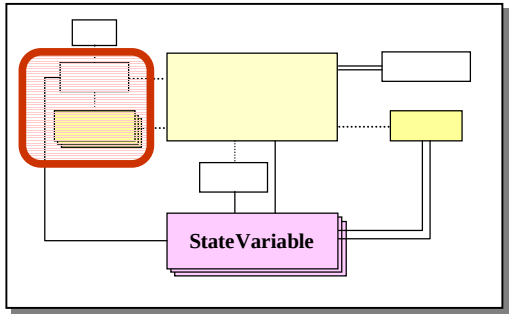
Defining Elaborators

- Default elaborators with GEL

```
(defGoal MyGoal (args)
  (between begin end)

  (tactic MyFirstTactic

    (goal MySubGoal1 (args)
          (between nameTP1 beginTP) )
    (timeConstraint nameTP1 beginTP
                    10 20)

    (goal MySubGoal2 (args)
          (between beginTP endTP) )
    (timeConstraint beginTP endTP 5 15)

  ) // MyFirstTactic
) // MyGoal

(def tp1 (mkTimepoint tp1))
(def tp2 (mkTimepoint tp2))
(elaborate (mkGoal MyGoal (args)
                   (between tp1 tp2)))
```

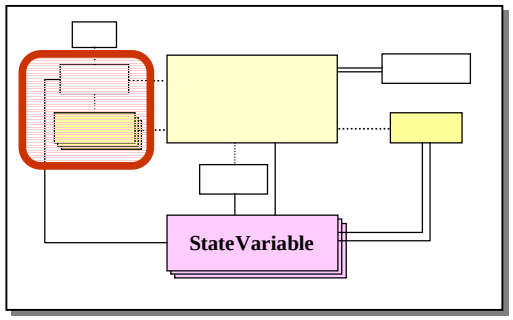
- Custom elaborators with C++

```
class MyFirstTactic : public Tactic
{
  ElaborationSpec* expand(TimePoint* beginTP,
                          TimePoint* endTP)
  {
    addGoal(new MySubGoal1(),
            "nameTP1", beginTP);
    addTemporalConstraint(10, 20, "nameTP1",
                          beginTP);

    addGoal(new MySubGoal2(),
            beginTP, endTP);
    addTemporalConstraint(5, 15,
                          beginTP, endTP);
  }
};


class MyGoal : public Goal<BasicElaborator>
{
  Goal()
  {
    addTactic(new MyFirstTactic() );
    addTactic(new MySecondTactic() );
  }
};
```



Backtracking

- When an elaborator fails to elaborate
  - Scheduling/propagation fails
  - Cannot find a Tactic that works
- Reports failure to its parent
- Parent can tell a sibling of the failed Elaborator to re-elaborate
  - Doing things a different way could clear up conflicts with the sibling's elaboration
- Then tell the failed Elaborator to "try again"
- Can do this for all SubGoals



Backtracking

Communicating Elaborator

elaborate

elaborate

Turn Elaborator

Maintain attitude Elaborator

elaborate

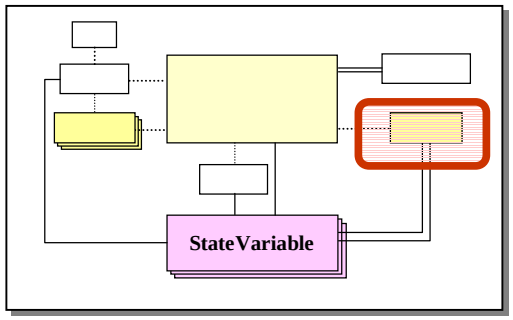
Thrust Elaborator

elaborate

elaborate

TransitionTemp 10°-20° C Elaborator

MaintainTemp 10°-20° C Elaborator

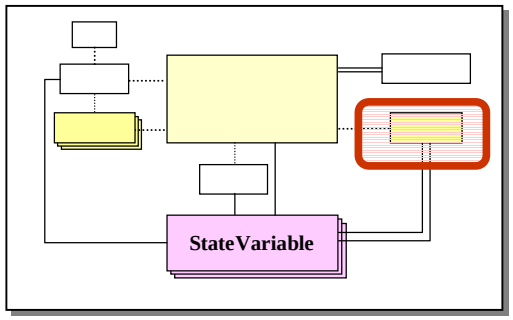


Goal Net Scheduling

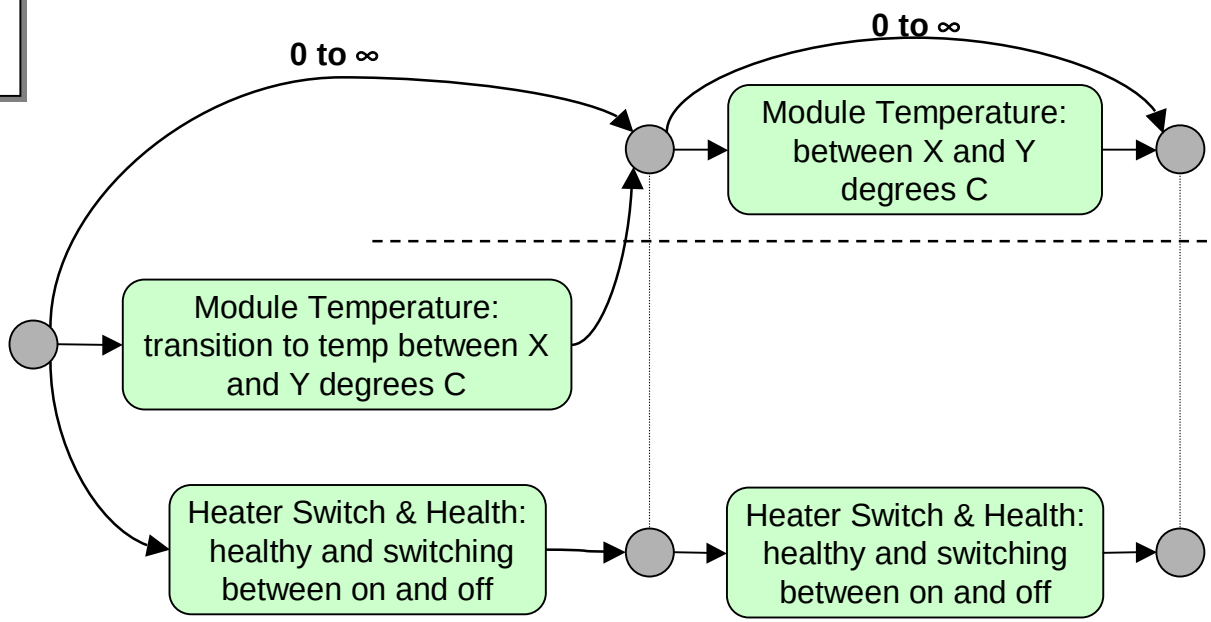
- Objective
  - To merge goals into executable x-goals
- Algorithm (used during promotion)

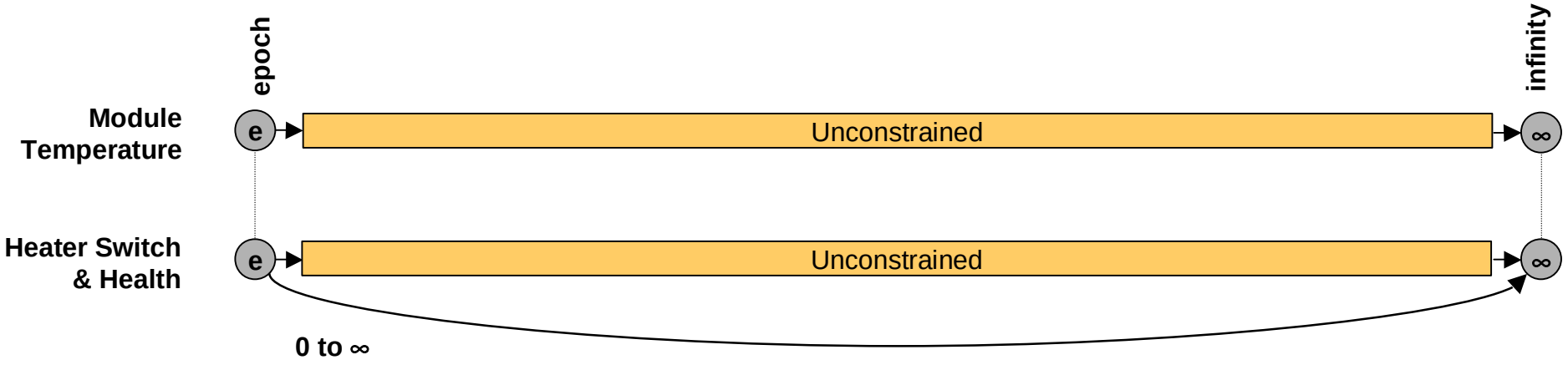
For each state variable **SVAR** (from a heuristic ordering) do
  For each new goal **G** on **SVAR** (from a heuristic ordering) do
    Exhaustively choose **G**'s constrained start timepoint **S**
    Exhaustively choose **G**'s constrained end timepoint **E**
    Merge **G**@[**S**,**E**] into **SVAR**'s timeline – Backtrack if merge illegal
  Propagate the expected behavior of **SVAR** given the goals
    – Backtrack if the propagation illegal

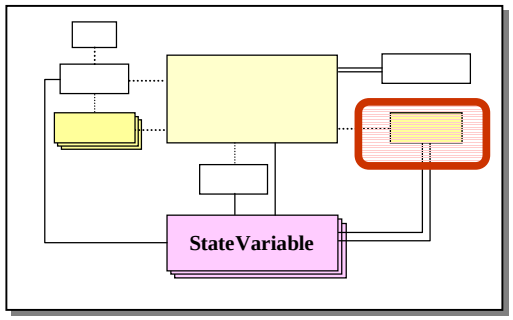
Replace executing task network with proposed one if it scheduled



Computing X-Goals







Computing X-Goals

0 to ∞

0 to ∞

Module Temperature: between X and Y degrees C

Module Temperature: transition to temp between X and Y degrees C

Heater Switch & Health: healthy and switching between on and off

Heater Switch & Health: healthy and switching between on and off

epoch

infinity

Module Temperature

e

0 to ∞

Unc.

Module Temperature: transition to temp between X and Y degrees C

0 to ∞

Unconstrained

∞

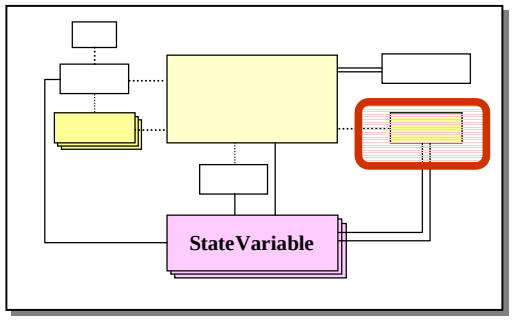
Heater Switch & Health

e

Unconstrained

∞

0 to ∞



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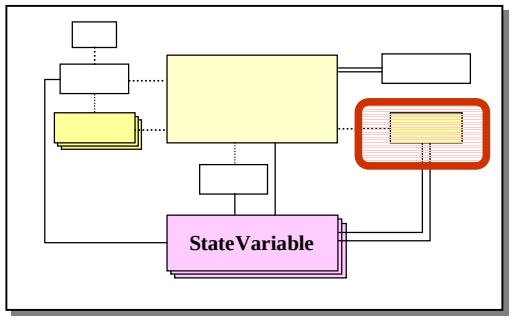

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Propagation tests

epoch

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Heater Switch & Health

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Unconstrained

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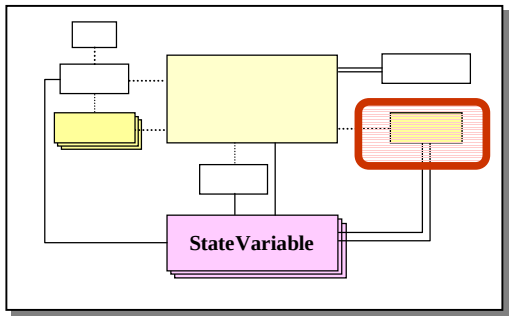

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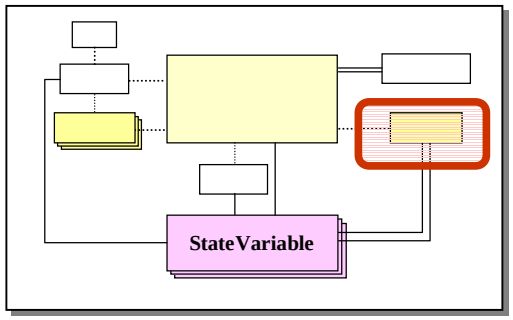

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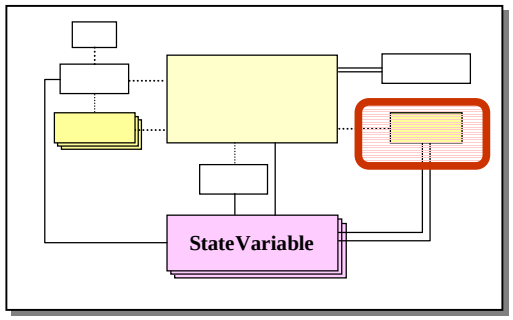

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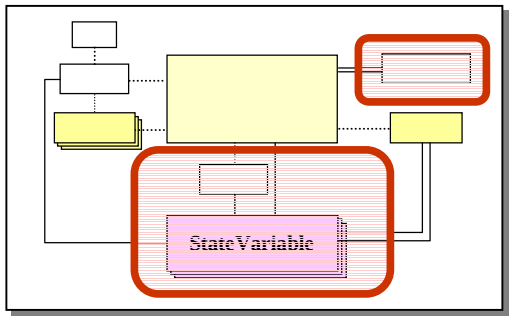
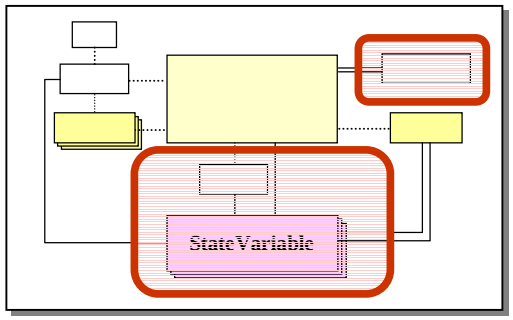


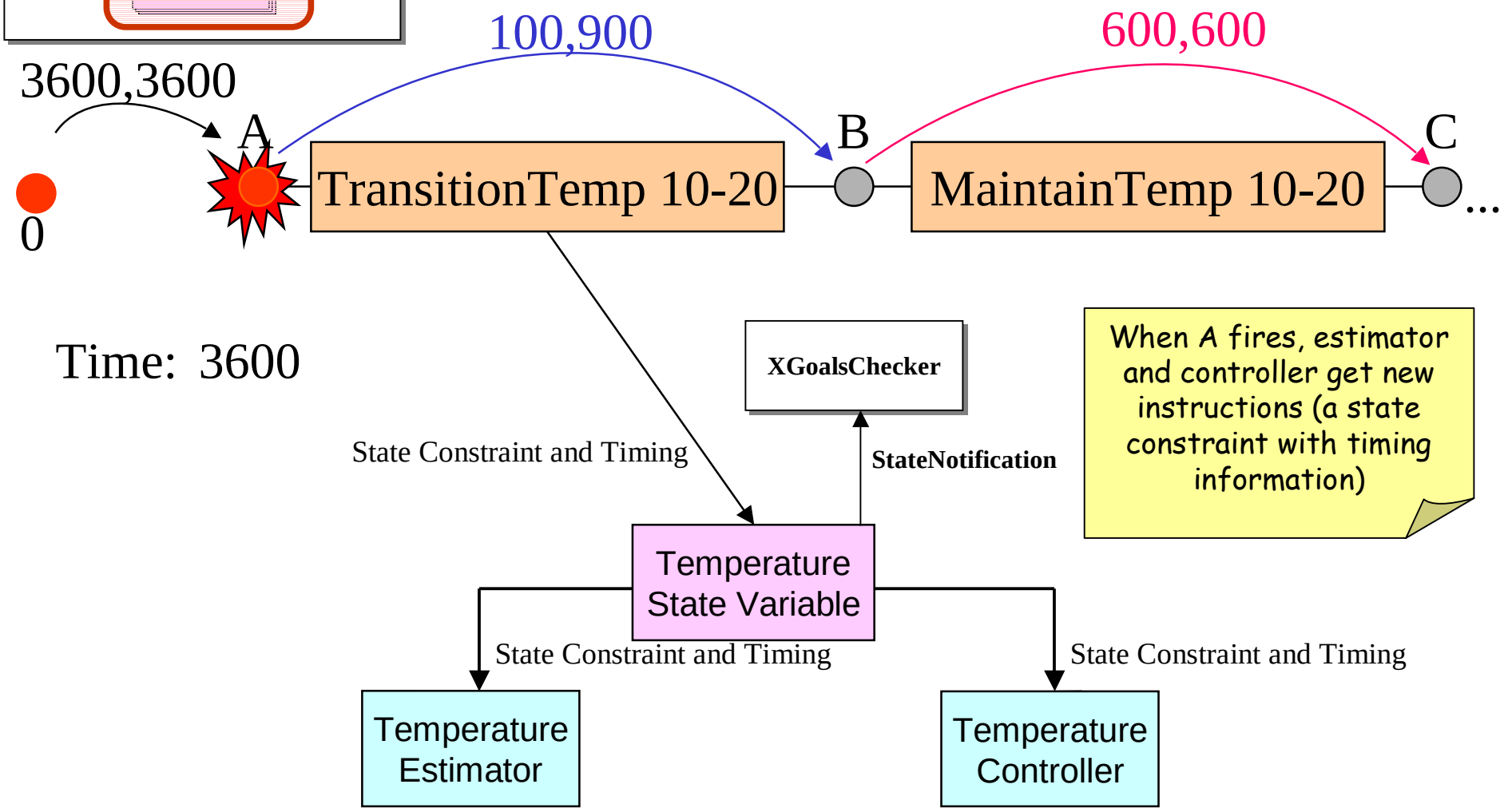
Goal Net Execution

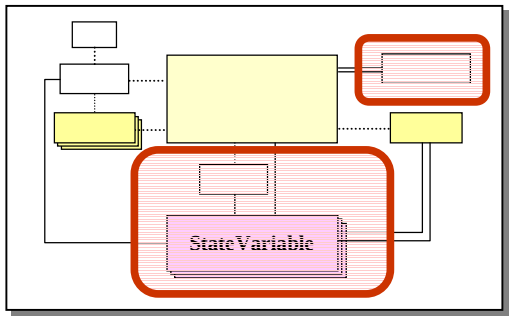
- Objective
  - ➢ To feed x-goal constraints to state variable controllers as temporal constraints require and circumstances permit.
- Algorithm

For each unfired timepoint **TP** not temporally constrained into the future do
If **TP**'s x-goals are ready to start or **TP** is about to time out then (fire)
For each x-goal **G**@[**TP**,*] respectively do
Send "start[**G**]" to **G**'s state variable's controller & estimator
Inform **G**'s parent goals to start or stop monitoring **G**'s status

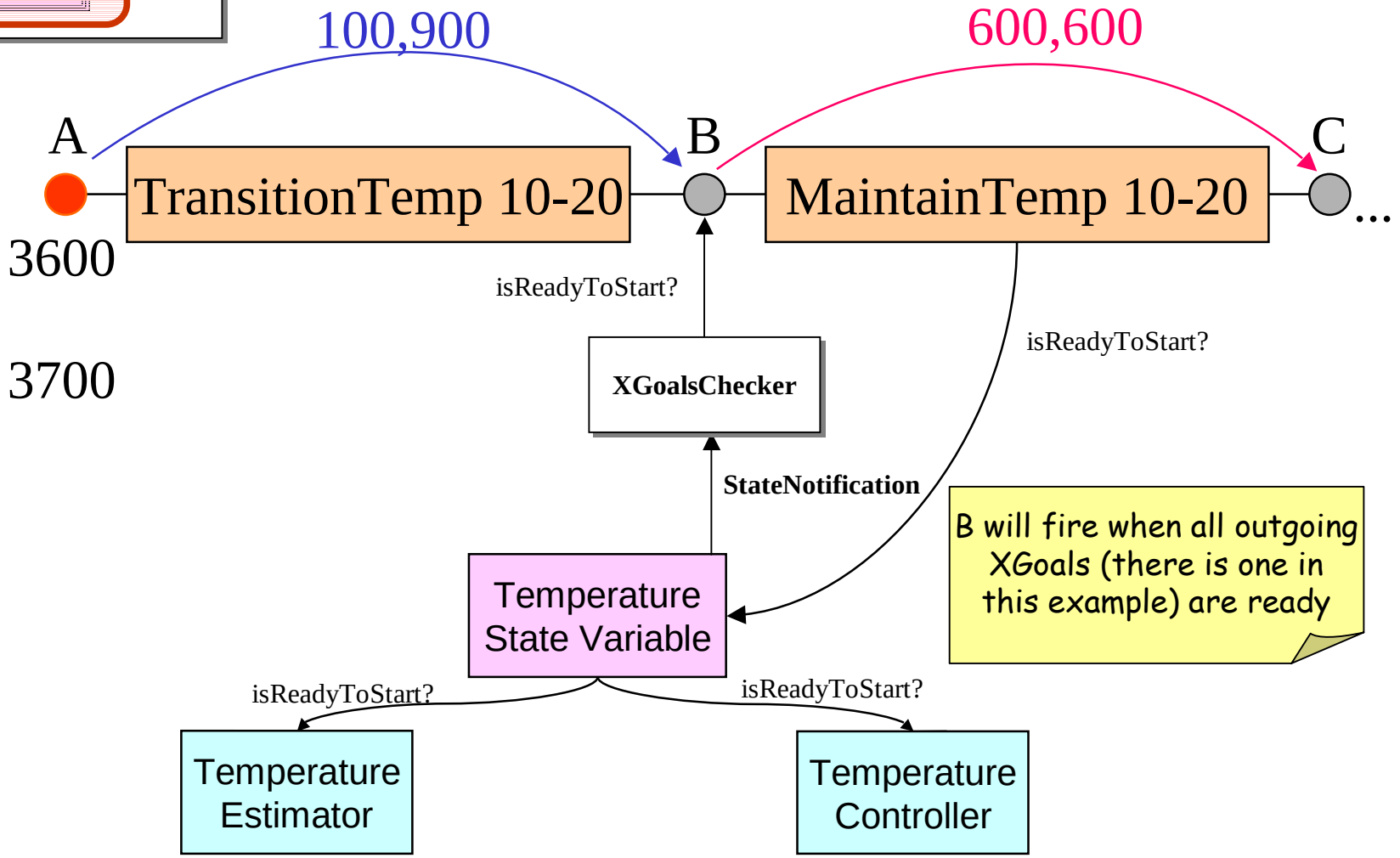


Timepoint A Fires

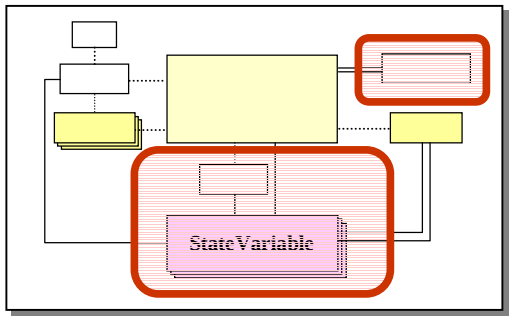




100 Seconds Later, Start Conditions are Monitored



Time: 3700



Timepoint B Fires

100,900

600,600

A

B

C

TransitionTemp 10-20

MaintainTemp 10-20

...

3600

3950

stop

Time: 3950

New state constraint replaces previous one in controller and estimator

XGoalsChecker

StateNotification

State Constraint and Timing

B will fire when temperature gets in range

Temperature State Variable

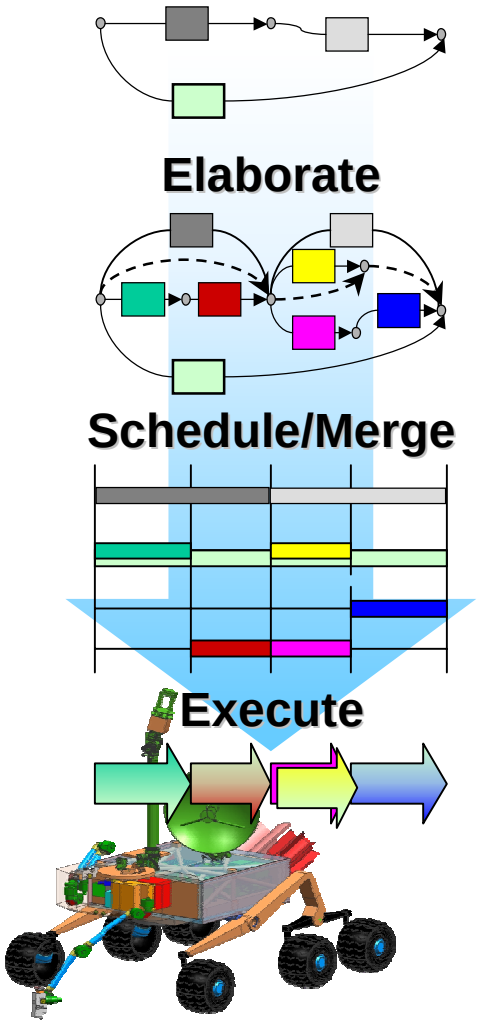
State Constraint and Timing

State Constraint and Timing

Temperature Estimator

Temperature Controller

Putting It All Together: a high-level characterization of current MPE algorithm



- Elaboration algorithm

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- Scheduling algorithm (used during promotion)

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      Inform **G**'s parent goals to start or stop monitoring **G**'s status

Next Steps in the Core

- Prioritized and delayed scheduling
  - Currently elaboration/scheduling just succeeds or fails.
  - Plan to break up commanded task subnet into a set of smaller prioritized subnets to elaborate and schedule in priority order. Subnets that fail to schedule persist for subsequent elaboration/scheduling attempts.
- State affects reasoning
  - Currently the side effects of commanded/elaborated constraints are not modeled.
  - Plan to embed a state-effects model into the system and use it to account for side effects during scheduling.

Observations

- The focus is on controlling to enforce constraints on state variables.
  - As opposed to the operator focus in AI planning.
  - Facilitates a clear way to merge concurrent action.
- The use of components and elaboration tasks enables a surprising amount of flexibility.
  - GEL can be used, but other approaches to elaboration are possible (in the same implementation).
  - The scheduler component can easily be replaced.
- Lifted time is the default, but it is not necessary.

References

- See:

http://mds.jpl.nasa.gov/outreach/